PERFORMANCE AND ACOUSTIC ANALYSIS OF A SMALL WIND TURBINE USED WITH A HELICAL PUMP FOR LIVESTOCK WATERING

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ABSTRACT

A helical pump powered by a small wind turbine with two different rotors (2.77 and 3 meter rotor diameters) was tested at 3 pumping depths (50, 75, and 100 meters). A high sound pressure level (SPL) of 70 to 85 decibels was produced for the 3 meter diameter wind turbine in the wind speed range of 10 to 16 meters/second (10 meter height), and the high SPL was caused by blade fluttering. A shorter (2.77 meter) blade rotor was tested and although high SPL was delayed to a higher wind speed, the wind turbine SPL still exceeded 80 decibels. The high SPL for both rotors could be prevented with a balancer load added to the control system. At a 75 meter pumping depth, the helical pump with a small wind turbine was shown to perform better than a centrifugal pump with a small wind turbine or a piston pump with a mechanical windmill.

INTRODUCTION

Farmers and ranchers need to water their livestock as reliably and as inexpensively as they can in order to be competitive in the global marketplace. Mechanical windmills with piston pumps have pumped water for livestock very reliably and inexpensively for over a hundred years. However, the cost of mechanical windmills and the maintenance of the piston pump have increased steadily over the past few decades. Testing at the USDA-ARS laboratory near Bushland, TX has shown that for a 30 m pumping depth a 2.44 m diameter small wind turbine on a 20 m guyed pipe tower with a smart controller and a 10-stage centrifugal pump can perform better than a 2.44 m diameter mechanical windmill on a 10 m windmill-type tower with a piston pump and the wind-electric system will also cost 25% less (Vick, 1997). However, it was also shown that a 3 m diameter wind turbine (18.5 m hub height) with a 19-stage centrifugal pump at a 73 m pumping depth could only pump about half as much water as a 3 m diameter mechanical windmill (10 m hub height) with a piston pump during the low wind months of the summer (Vick, 1999). Recently Grundfos[1] designed a helical pumping system which could be powered by solar-PV power or wind power. A helical pump (positive displacement) should have higher flow rates at deeper pumping depths with lower power requirements than a centrifugal pump. Grundfos recommends using a Southwest Windpower[1] H-80 wind turbine (3 m diameter) with its helical pumping system. The Grundfos helical pump selected was the Model 6 SQF-2 and data were collected at 50, 75, and 100 m. Data were also collected for this same pump at these same pumping depths, but solar-PV modules were used as the power source and that performance analysis will be reported in another paper (Vick, 2005).

[1] The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA – Agricultural Research Service.

Test Setup, Instrumentation and Data Acquisition

The H-80 wind turbine was installed on an existing 19.2 m (63 ft) tilt-up guyed pipe tower and data collection on wind turbine and pumping performance began in Nov., 2003 (Fig. 1).

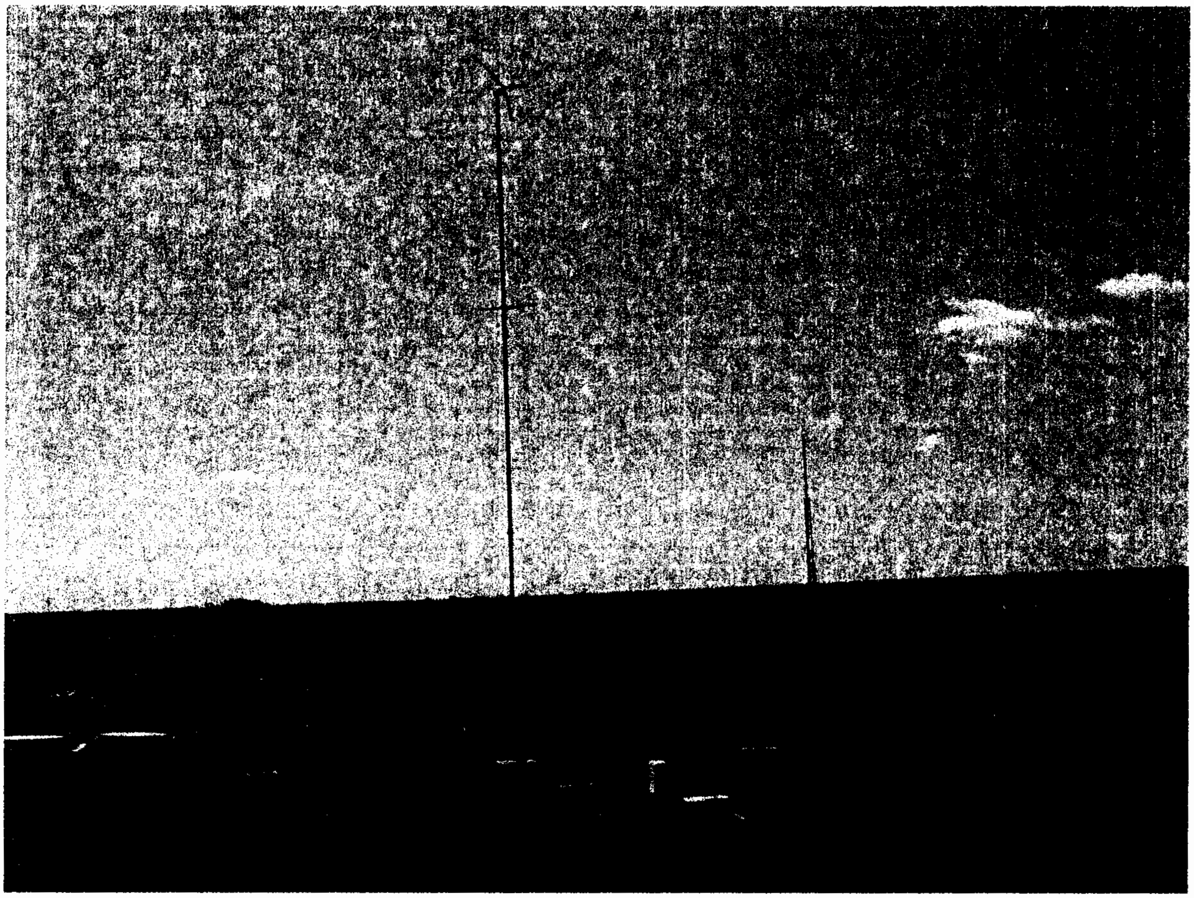

Fig. 1. Southwest Windpower H-80 mounted on a 19.2 m tilt-up guyed pipe tower (Bushland, TX).

For water pumping performance the wind speed was measured with a Met-One[1] Model 014 cup anemometer mounted on a tower located 120 m WNW of the wind turbine. The wind speed measured by this anemometer was calibrated to give the hub height wind speed of a wind turbine installed on the 19.2 m tower (Vick, 2003). Wind direction for water pumping performance was obtained from a Climet[1] (now sold by Met One) Model 011 transducer located on a tower 123 m NNW of the wind turbine. Because of a hill and buildings located north of the wind turbine, only data in the wind direction range of 90 to 270 degrees were processed. The H-80 wind turbine outputs variable voltage/variable frequency 3-phase AC electricity which is rectified to DC in a control system supplied by Grundfos before it is connected to the helical pump motor. This Grundfos control system (Model CU 200) also communicates with control circuitry located in the metal casing of the submersible helical pump motor to determine if the input electricity is DC or single-phase AC. Other controller functions are to determine if input power is sufficient to pump water and also to determine if well water level is too low to pump water. The power to the motor from the wind turbine can also be shutoff manually by pushing the on/off button.

AC power was collected for the wind turbine using a Flex Core[1] Model P-144X5 transducer and a CR Magnetics[1] Model CR 6230-250-5 transducer. AC Voltage was measured with a Rochester Instruments[1] Model VCC-1B transducer. The transducer used to measure the electrical frequency of the wind turbine was built by WTAMU-AEI personnel. The DC Voltage and DC Current measured between the controller and the helical pump motor were measured with CR Magnetics transducers -- Models CR 5310-500 and CR 5210-50, respectively. The water flow rate was measured with a Hersey[1] Model 30 flow meter and the water pressure was measured with a Honeywell[1] Model EA transducer. All of the data discussed above was sampled every second on a Campbell Scientific[1] 23X data logger and the average values were stored every minute on a storage module. These data were downloaded to a PC on a weekly basis and then the data were processed with a Quick Basic[1] computer program which binned the data according to wind speed.

We felt the sound level of this wind turbine was excessive when the wind speed exceeded 10 m/s due to the blades fluttering, so a type 1 Larson Davis[1] Model 824 sound level meter (SLM) was purchased along with other Larson Davis equipment -- calibrator (Model CAL200), microphone (Model 2541), 1.8 m (6 ft) of cable connecting the microphone to SLM, and software for processing acoustic data. In addition, foam for primary and secondary wind screens was purchased. The wind turbine noise standard IEC 61400-11 (IEC, 2002) and another paper (Migliore, 2004) were used as references in the acoustic collection of data and analysis of the H-80 wind turbine. The wind speed and wind direction for acoustic measurements was collected every second with a R.M. Young[1] Model 81000 sonic anemometer on a portable 10 m height tower located 3.5 rotor diameters SW of wind turbine tower (prevailing wind is from SW). The procedure used in the acoustic data collection was as follows:

1. Check the calibration of the Model 824 Larson Davis SLM with a calibrator.
2. Synchronize the clocks of the Campbell 23x data logger and the Larson Davis 824 SLM.
3. Place the microphone of SLM under windscreen(s) on a 1.22 m (48 in) diameter 1.9 cm (0.75 in) thick cylindrical piece of plywood (soundboard) which was located downwind of the tower (tower height[2] + ½ blade rotor dia. = 20.7 m) and begin one-second data collection on both meters (Campbell and Larson Davis).
4. With wind turbine braked (i.e. phases shorted) and using only primary wind screen, collect at least 30 minutes of background noise. The diameter of the primary wind screen chosen was 17.8 cm (7 in) which was double that specified by the IEC 61400-11 noise standard, but this diameter was chosen since this was the wind screen size used by NREL in their acoustic testing for small wind turbines (Huskey, 2004).
5. Collect 30 minutes of background noise with both primary and secondary wind screens – the secondary wind screen was 61 cm (24 in) in outside diameter and was 1.9 cm (0.75 in) thick with porosity of 6 pores/10 mm.
6. Release brake and collect at least 30 minutes of data with wind turbine running and using both primary and secondary wind screens. A cautionary note – if the wind turbine is released in wind speeds above 9 m/s (hub height) then it could take half an hour or more

[2] Should have been from ground to center of rotor hub position, but this small error (0.30 m) is within tolerance specified by IEC 61400-11.

for the wind turbine to synchronize with the helical pump.

7. Remove secondary windscreen and collect at least 30 minutes of data with wind turbine running and using just primary wind screen.
8. Stop one second data collection on SLM and data logger and check time of both to see if different.
9. Download data from data logger storage module and SLM to PC.
10. Make notes in log book on data collection.

Later, sound data with extraneous noise measurements of birds, airplanes, vehicle noises were filtered or deleted according to notes in log book and also by analyzing time series of sound pressure level, wind speed, and rotor speed in a spreadsheet program. After all the bad data points were removed or filtered, the Larson Davis A-weighted SPL data (1-second averages) were merged with the Campbell 23x data (1-second averages). According to IEC 61400-11 the data averages were to be over at least one-minute, but since the SPL increased significantly when the blades began fluttering at a certain rotor speed, we used a smaller time average – acoustic testing of small wind turbines at NREL for similar reasons decided upon a 10-second average (Migliore, 2004). Two Quick Basic programs were written to process the merged Campbell 23x and Larson-Davis 824 data. One program binned the A-weighted SPL data using the 10-meter height wind speed as the independent variable and the other binned the A-weighted SPL data using the rotor speed as the independent variable [Rotor Speed = 120 * frequency/ (# of poles)]. The A-weighted SPL data binned by wind speed were also corrected for background noise (IEC, 2002).

HELICAL PUMP PERFORMANCE ANALYSIS WITH A SMALL WIND TURBINE

Fig. 2 shows the measured flow rate for the H-80 wind turbine (3 m rotor diameter) with the helical pump at 3 different pumping depths (50, 75, and 100 meters) as a function of hub height wind speed. The cut-in wind speed varied between 4.5 and 5 m/s. The flow rate remained relatively constant above a wind speed of 8 to 10 m/s (depending on pumping depth).

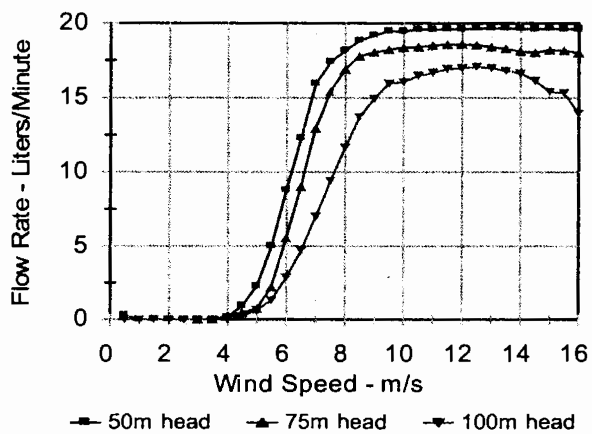

Fig. 2. Measured Flow Rate of H-80 Wind Turbine with Grundfos 6 SQF-2 Helical Pump (Bushland, TX).

Fig. 3 shows a flow rate comparison of a small wind turbine (Bergey[1] 1500, 3.05 m rotor dia.) with a centrifugal pump (19 stages, 0.75 kW), a mechanical windmill (Dempster[1] 3.05 m rotor dia.) with a 4.8 cm diameter piston pump, and a small wind turbine (Southwest Windpower H-80, 3 m rotor dia.) with a helical pump (6 SQF-2). The cut-in wind speed of the wind turbine/helical pump is between that of the windmill with a piston pump and that of a wind turbine with a centrifugal pump. The maximum flow rate is highest for centrifugal pump, helical is next highest, and piston is lowest. In fact, depending on how much high winds occur above 14 m/s, the wind turbine with centrifugal pump can get as high as 38 liters/minute at 13 m/s.

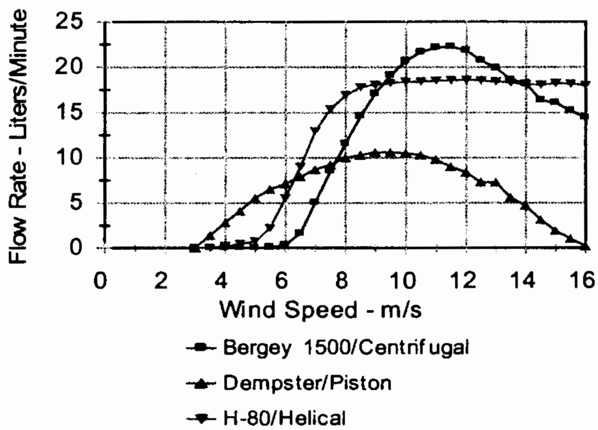

Fig. 3. Effect of Pump Type on Flow Rate for 75 m pumping depth (same 3 m rotor diameter).

Using the flow rate in Fig. 2 and the wind distribution for Bushland, TX in 1998 (18.5 m height), the daily water volume was calculated and is shown in Fig. 4. The 1998 wind distribution at Bushland was chosen for all the daily water volume comparisons since that was the distribution used in the Windpower 1999 paper (Vick, 1999), and some of the graphs from that paper were published in a book (Gipe, 2004). Assuming each cow requires 50 liters of water per day in August, the H-80 with the helical pump can water 80, 120, and 160 cattle for pumping depths of 100, 75, and 50 m, respectively.

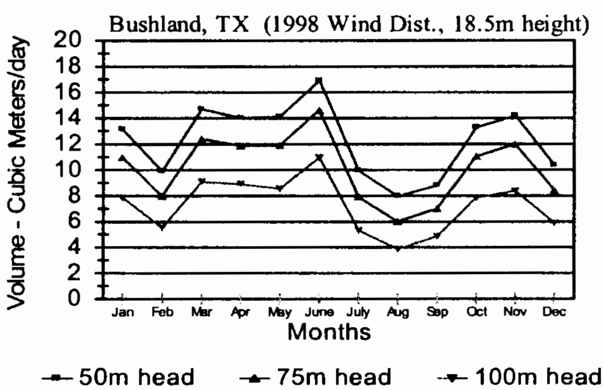

Fig. 4. Average Daily Water Volume of H-80 wind turbine with a Grundfos 6 SQF-2 Helical Pump.

Using the flow rate in Fig. 3 and wind distributions for Bushland, TX in 1998 (10 and 18.5 m), the daily water volume for the different pumps for a 75 m pumping depth is shown in Fig. 5. It should first be noted that the windmill has a hub height of 10 m while the wind turbines are at a hub height of 18.5 m. Because the wind turbine towers are so much less expensive than the mechanical windmill tower, it makes no sense to install them at the windmill height (Vick, 1997). The small wind turbine (Bergey 1500) with the centrifugal pump matches the daily water volume of the mechanical windmill with the piston pump except for the months July, August, and September when the wind speed is the lowest (Vick, 1999). However, when a small wind turbine (Southwest Windpower H-80) is combined with a helical pump, the daily water volume during the low wind summer months is about the same as the windmill with the piston pump, and for other months of the year is always higher than the mechanical windmill by 2000 to 5000 liters. The 3 m rotor diameter wind turbine with the helical pump pumps 2000 to 4000 liters more water per day than the 3 m rotor diameter wind turbine with the centrifugal pump.

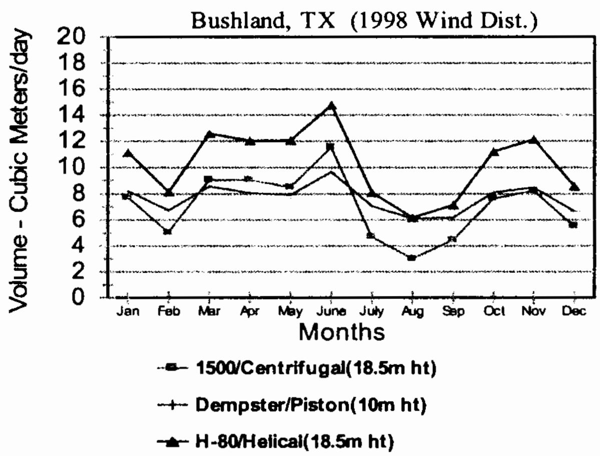

Fig. 5. Effect of Pump Type on Daily Water Volume (3m rotor diameter, 75m pumping depth).

H-80 WIND TURBINE ACOUSTIC ANALYSIS

As mentioned before, when testing first began on the H-80 wind turbine with the helical pump in Nov. 2003 at Bushland, it was observed that the sound level produced by the wind turbine was objectionable to most people at the laboratory. Instrumentation (sound level meter, microphone, calibrator, wind screen foam) were later purchased in order to measure the sound pressure level of the wind turbine according to IEC 61400-11. According to IEC 61400-11 noise standard, a secondary wind screen is required for high winds, but high winds are not defined. However, since the standard wind speeds for which data were required were 6, 7, 8, 9, and 10 m/s then one could conclude high winds were wind speeds above 10 m/s. Since the wind turbine was observed to produce excessive noise above 10 m/s then only the data with both primary and secondary wind screens are shown. The sound level meter microphone was located a distance of 20.7 m from the base of the tower. Fig. 6 shows as a function of wind speed the SPL of the background (no H-80 wind turbine operating, e.g. H-80 braked), the SPL of the H-80 with a 3 m rotor, and SPL of H-80 with 2.77 m rotor. The SPL of the wind turbine was corrected for background SPL according to IEC 61400-11. The background SPL is higher than what would normally be expected because of the sound emanating from another wind turbine[3] (Enertech E-44) which was located 130 m downwind of the H-80 wind turbine. The 10 m height wind speed was not corrected to the "standardized wind speed" in IEC 61400-11 due to calculation of different roughness lengths at each wind speed (modifying a 10 m height wind speed with a roughness length dependent on wind speed does not seem correct). The smaller 2.77 m diameter rotor did not produce as much SPL as the 3 m diameter rotor until a higher wind speed was reached. For instance, a SPL of 70 dB occurred at a wind speed of 10 m/s for the 3 m rotor while the same SPL occurred at a wind speed of 12.7 m/s for the 2.77 m rotor. Also, the standard deviation of the measured sound pressure level was very high for both rotors 4 to 12 dB.

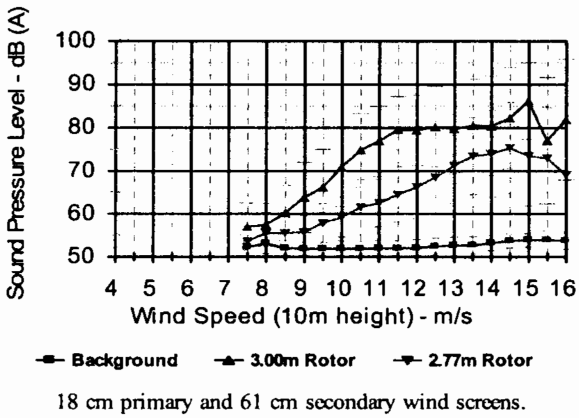

Fig. 6. Measured Sound Pressure Level of H-80 Compared to Background Noise at Bushland, TX (Wind Speed Binned).

The measured noise data for the two rotors shown in Fig. 6 were binned in terms of rotor speed instead of wind speed and the result is shown in Fig. 7. Besides the standard deviation decreasing significantly for both rotors, the sound pressure significantly increases for the 3 meter rotor from 730 rpm (~ 61 Hz) to 760 rpm (~ 63 Hz), and for the 2.77 m rotor the sound pressure significantly increases from 950 rpm (~ 79 Hz) to 1000 rpm (~ 83 Hz).

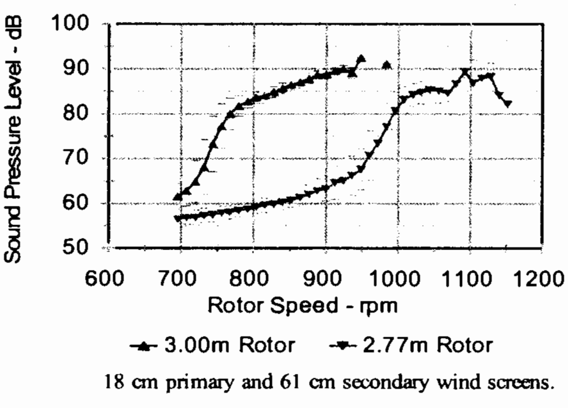

Fig. 7. Effect of H-80 Blade Rotors on Sound Pressure Level (Rotor Speed Binned).

[3] Enertech E-44 (13.4 m rotor diameter, downwind wind turbine) increases background SPL 8 to 10 dB and cut-in wind speed for E-44 occurs at a wind speed of 7.5 m/s at a 10 m height.

So as long as the rotor speed never exceeds 684 rpm (57 Hz) on the 3 m rotor and 900 rpm (75 Hz) for the 2.77 m rotor, the SPL will be much lower.

H-80 POWER CURVE MEASUREMENT

Before making a comparison of the AC power measured for each of the pumping depths, it is worthwhile to look at two common ways used for correcting measured higher altitude wind turbine power data to sea level standard day (SLSD) conditions. If the wind speed is held constant and the power is corrected then the following equation is used.

$$P_{SLSD} = (\rho_{SLSD}/\rho_{meas})\, P_{meas} \qquad (1)$$

Where P_{SLSD} is power at SLSD conditions (W)
ρ_{SLSD} is air density at SLSD conditions (1.225 kg/m^3)
ρ_{meas} is measured air density (kg/m^3)
P_{meas} is measured power (W)

However, another way of correcting to SLSD conditions is by using the following equation which holds the power constant and corrects the wind speed.

$$V_{SLSD} = V_{meas}\, (\rho_{meas}/\rho_{SLSD})^{1/3} \qquad (2)$$

Where V_{SLSD} is wind speed at SLSD conditions (m/s)
V_{meas} is measured wind speed (m/s)
ρ_{meas} & ρ_{SLSD} are same as before

Fig. 8 shows a comparison of measured power, correction of power to SLSD with equation 1, and correction of power to SLSD with equation 2. We intuitively feel that correcting the wind speed to SLSD is more accurate for a furling wind turbine because a furling wind turbine should furl at a lower wind speed at SLSD conditions which implies the maximum power will be less than that resulting from using equation 1.

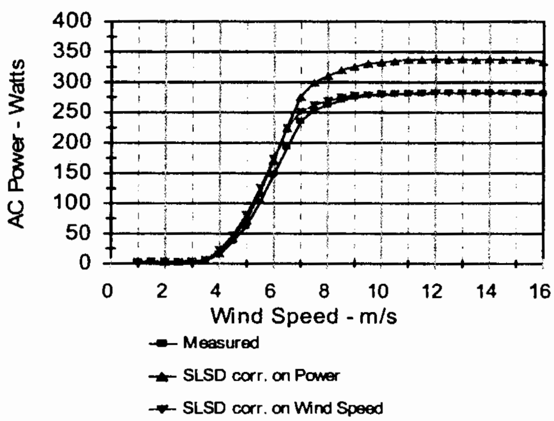

Fig. 8. Comparison of Different Ways of Correcting Power Curve to Sea Level Std. Day (Measured at Bushland, TX for H-80 with 6 SQF-2 Helical Pump at 50 m head).

Fig. 9 shows the SLSD power of the H-80 wind turbine connected to the helical pump at Bushland, TX and the SLSD power of the H-80 wind turbine connected to a battery array via two Trace[1] C40 inverters in Tehachapi, CA. The Bushland data are shown for three different pumping depths (50, 75, and 100 m). It is obvious from this graph that even at the 100 m pumping depth; the H-80 wind turbine is underloaded at wind speeds above 9 m/s which results in the higher sound level at these higher wind speeds. Therefore, if a balancing electrical load was applied at a certain frequency; high sound pressure levels should be prevented.

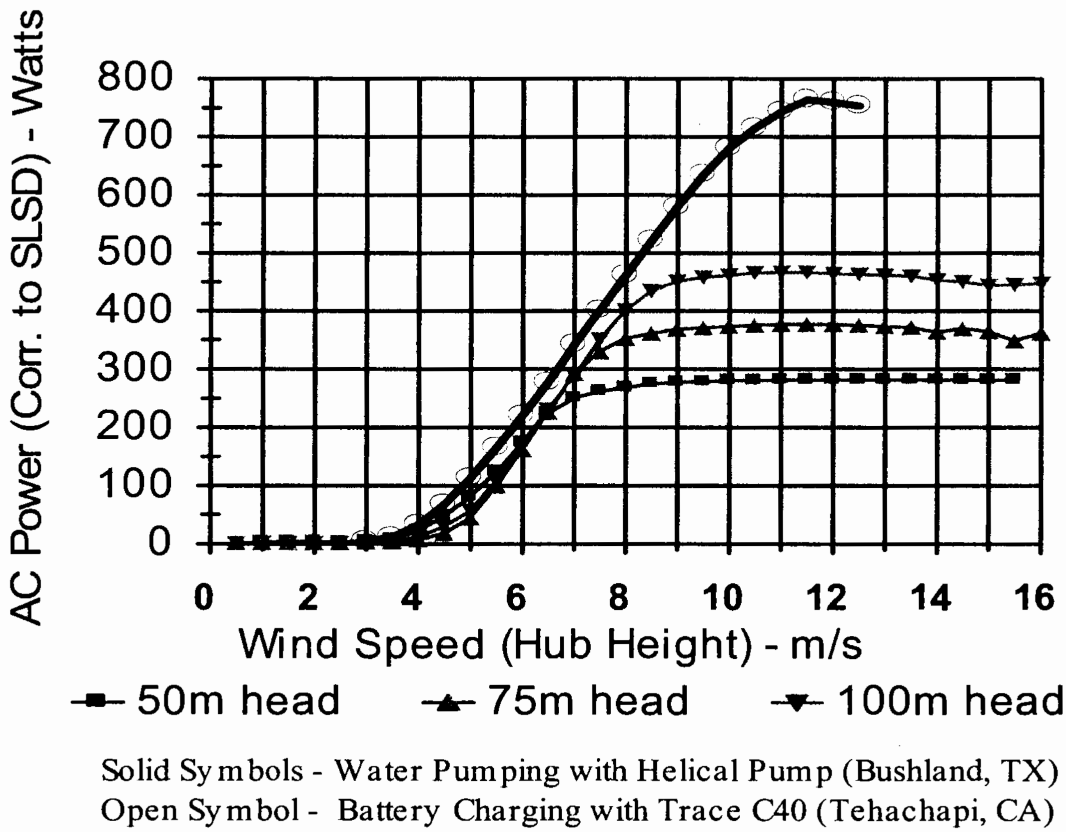

Fig. 9. H-80 Power Curve Comparison of Battery Charging to Helical Pump Water Pumping.

CONCLUSIONS

Even with the shorter diameter H-80 blades (2.77 m compared to 3 m), there still will be a high sound pressure level for this remote small wind turbine powered helical water pump system when the wind speed at a 10 m height exceeds 12.7 m/s due to underloading of the H-80 rotor by the helical pump. However, both rotors should not produce a high sound pressure level if a balancer load is added to the controller. The balancer load (resistors, inductors, and/or capacitors) would be applied at a frequency (57 Hz for 3 meter diameter rotor, 75 Hz for 2.77 m diameter rotor) in order to load up the wind turbine and keep the blades from fluttering. For a pumping depth of 75 m, a helical pump performs better than a centrifugal pump for a 3 m diameter rotor wind turbine. Replacing a mechanical windmill/piston pump system with a wind turbine/helical pump system is a good idea for a pumping depth of 75 m. Reliability of the wind-electric helical pump system appears very good so far (no downtime after 1.5 years of testing at Bushland, TX).

ACKNOWLEDGEMENTS

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